

Recent Results from PHENIX Experiment at RHIC: Exploring the QCD Medium

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Abstract

We review some important results from the PHENIX experiment at RHIC. They were obtained in a unique environment for studying QCD bulk matter at temperatures and densities that surpass the limits where hadrons exist as individual entities, so raising to prominence the quark-gluon degrees of freedom. We present measurements of nuclear modification factors for neutral pions, light favors (strange hadrons), direct-photons and non-photonic electrons from decays of particles carrying charm or beauty quarks. We interpret the large suppression of hadron production at high transverse momenta as resulting from a large energy loss by the precursor parton on its path through the dense matter, primarily driven by gluon radiation. This dense QCD matter responds to energy loss in a pattern consistent with that expected from a hydrodynamic fluid. Further, its elliptic flow measurements suggest that the hadronization of bulk partonic matter exhibits collectivity with effective partonic degrees of freedom. The results are shown as a function of transverse momentum, centrality in different collision systems and energies.

Key words: Jet quenching, di-jet correlations, bulk collectivity, silicon vertex tracker upgrade

PACS:

1. Physics motivation and RHIC achievements

Quantum Chromodynamics (QCD) is considered the fundamental theory for strong interactions. According to it, hadronic matter under extreme dense, hot conditions must undergo a phase transition [1] to form a Quark Gluon Plasma (QGP) in which quarks and gluons no longer are confined to the size of a hadron. Recent results from lattice QCD at finite temperature [2,3] reveal a rapid increase in the number of degrees of freedom associated with this deconfinement of quarks and gluons from their hadronic chains. The transition point is at a temperature $T \approx 170$ MeV and energy density of $\epsilon \approx 1$ GeV/fm³. Under the same conditions, chiral symmetry is restored [2]. Therefore, our experiments search for signatures of both QGP formation, and the in-medium effects of the hadrons' properties. Purportedly, these required high densities could be achieved via relativistic heavy ion collisions [4].

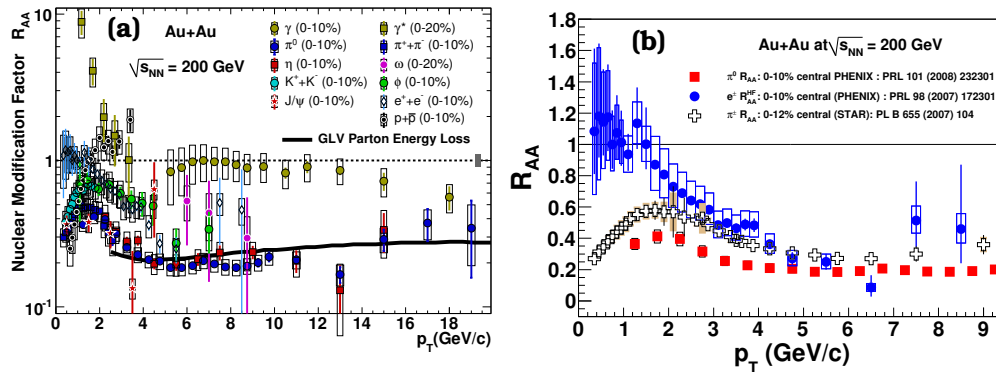


Fig. 1. Compilation of data of nuclear modification factor R_{AA} from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5]. Panel (a) nuclear modification factor, R_{AA} , for identified particles measured by PHENIX, given as a function of transverse momentum, p_T . The continuous curve corresponds to the GLV theory [6]. Panel (b) represents the nuclear modification factor of heavy-flavor electrons R_{AA}^{HF} compared with the R_{AA} of π^0 and π^\pm .

Under the RHIC (Relativistic Heavy Ion Collider) project, an accelerator was constructed at Brookhaven National Laboratory (BNL) from 1991 to 1999. RHIC was designed as a heavy-ion machine, that would support the collision of a wide range of nuclei over a large range of energies. Already, gold-gold, copper-copper and deuteron-gold collisions were attained at energies from $\sqrt{s_{NN}} = 7.7$ to 200 GeV. Further, a polarized capability was added to RHIC allowing transverse and longitudinal polarized protons to collide at energies from $\sqrt{s_{NN}} = 200$ to 500 GeV. Earlier, RHIC researchers made a major physics discovery, namely the creation, in high-energy central gold-gold collisions, of a new form of matter, dense and strongly interacting, called the strongly coupled quark-gluon plasma, or sQGP. This finding was rated the top physics story of 2005; the four experiments at RHIC, BRAHMS, PHENIX, PHOBOS, and STAR, published, evidence of the existence of this new form of matter [7,8]. The RHIC accelerator also met and surpassed its specifications; namely, it attained its energy goals, and exceeded, by a factor of 2, its heavy-ion luminosity goals, and its polarized proton luminosity by a factor of 5.

In this article, I highlight some of recent PHENIX experiment results underlying these major experimental observations. I start by discussing our hard-probe measurements; high- p_T hadron suppression, including heavy-flavors and di-jet fragment azimuthal correlations probes. These measurements of hard probes afford direct signatures of highly interacting dense matter created at the RHIC. I then present our measurements of elliptic flow that are an indirect signature of the existence of partonic matter. These measurements, for different particle species, are given as a function of collision centrality, energy, and system sizes.

2. High- p_T hadron suppression : Jet quenching

In heavy ion collisions (from AGS to RHIC energies) hadron production at the mid-rapidity region ($|y| < 1.5$) rises with increasing collision energy. At RHIC, the central zone is almost baryon free [9]. The large particle production is dominated by pair production, and the energy density seems to exceed significantly that required for QGP formation [7]. The PHENIX experiment revealed the suppression of the high transverse momentum

component, p_T of hadron spectra at the mid-rapidity region in central Au+Au collisions compared to the scaled momentum spectra from $p+p$ collisions at the same energy, $\sqrt{s_{NN}} = 200$ GeV [7]. This effect, originally proposed by Bjorken, Gyulassy and others [10] rests on the expectation of a large energy loss from high momentum partons scattered during the initial stages of collisions in a medium with a high density of free color charges. According to QCD theory, colored objects may lose energy by the Bremsstrahlung radiation of gluons [11]. Such a mechanism would strongly degrade the energy of leading partons, as reflected in the reduced transverse momentum of leading particles in the jets emerging after their fragmentation into hadrons. Figure 1 compiled the data [5] for the nuclear modification factors measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The nuclear modification factor is defined as:

$$R_{AA}(p_T) = \frac{d^2N^{A+A}/dp_T d\eta}{N_{bin} d^2N^{p+p}/dp_T d\eta} \quad (1)$$

It involves scaling the measured distributions of nucleon-nucleon transverse momentum by the number of expected incoherent binary collisions, N_{bin} [12]. In the absence of any modifications caused by the ‘embedding’ of elementary collisions in a nuclear collision, we expect $R_{AA} = 1$ at high- p_T . At low p_T , where particle production follows a scaling with the number of participants, the above definition of R_{AA} leads to $R_{AA} < 1$ for $p_T < 2$ GeV/c. Figure 1(a) summarizes the present status of R_{AA} for neutral pions, light favors (strange hadrons), direct-photons and non-photonic electrons from heavy quarks decays in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The R_{AA} for direct photons are not suppressed because they do not interact strongly with the medium. The R_{AA} for both π^0 and η ’s mesons exhibit the same suppression relative, by a factor of 5, to the point-like scaled $p+p$ data appear to be constant for $p_T > 4$ GeV/c, while the η mass is much larger than that of π^0 . This observation points to partonic nature of suppression. These data of R_{AA} were described by theoretical calculations of the partons’ energy loss in the matter created in Au+Au collisions [13]. From these theoretical frameworks, we learned that the gluon density dN_g/dy must be approximately 1000, and the energy density of the matter created in the most central collisions must be approximately 15 GeV/fm³ to account for the large suppression observed in the data [14,15].

PHENIX measured heavy flavor production via semi-leptonic decays, and identified electrons from the decays of D - and B -mesons. In the mid-rapidity region, electron identification largely is based on using the Ring Imaging Cherenkov detector (RICH), in conjunction with a highly granular electromagnetic calorimeter (EMC). Their momentum is derived from the curvature of the track (due to a magnetic field up to 1.15 Tesla) reconstructed from the drift and pad-chambers. A major difficulty in electron analyzes is that there are many sources of electrons, other than the semi-leptonic decays of heavy flavor mesons. Figure 1(b) compares the nuclear modification factor R_{AA} of heavy flavor electrons to π^0 data, and to the π^\pm data obtained from central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [5,16,17]. We observe clear suppression of heavy flavor electrons in central events in high- p_T . For $p_T > 4$ GeV/c, the R_{AA} of heavy flavors is surprisingly similar to that for π^0 and π^\pm .

An interesting result of the nuclear modification factor in heavy ion collisions concerns the ϕ meson, whose mass is close to that of a proton and Λ . The ϕ meson does not participate as strongly as others do in hadronic interactions, nor are ϕ mesons formed via the coalescence-like $K^+ + K^-$ process in high energy collisions [18]. Figure 2 (a), (b),

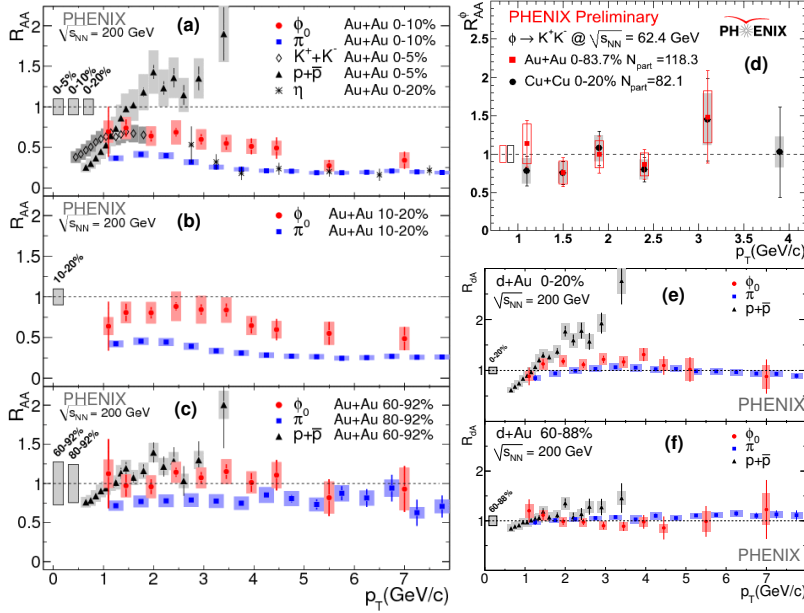


Fig. 2. Panels (a), (b), and (c) show the R_{AA} for different particle species obtained from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Panel (d) shows the ϕ R_{AA} for centrality bin selected such as the N_{part} is similar in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 62.4$ GeV. Panels (e) and (f) show the R_{AA} for different particle species, including the ϕ 's obtained from d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

and (c) show the R_{AA} for ϕ , π^0 , proton, kaon and η , all measured in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [19]. The ϕ mesons exhibit a different suppression pattern than the lighter non-strange mesons and baryons. For central collisions (Figure 2 (a)) the ϕ 's R_{AA} has less suppression than π^0 and η in the intermediate p_T range of $2 < p_T$ (GeV/c) < 5 . At higher p_T ($p_T > 5$ GeV/c), the ϕ 's R_{AA} approaches and becomes comparable to the π^0 and η 's R_{AA} . These features remain true for all centralities up to the most peripheral collisions, as displayed in Figure 2 (c). This panel shows that the π^0 is slightly suppressed in peripheral Au+Au collisions whereas the ϕ is not suppressed. The kaon data cover only a very limited range at low p_T ; nevertheless, in this range they seem to follow the R_{AA} trend of the ϕ better than that of π^0 and η for central Au+Au collisions. The comparison with baryons (protons and anti-protons) shows different pattern. For central collisions, the protons show no suppression but rather an enhancement at $p_T < 1.5$ GeV/c, whereas the ϕ mesons are suppressed. We observed the similarity of the R_{AA} of protons and ϕ mesons for most peripheral collisions.

Figure 2(d) compares the R_{AA} of ϕ in Au+Au- and Cu+Cu- collision in two centrality bins corresponding approximately to the same number of participants in the two systems. Under this condition, there is no difference in the R_{AA} of ϕ between the two systems, indicating that the level of the suppression, when averaged over the azimuthal angle, scales with the average size of the nuclear overlap, regardless of the details of its shape. Cold nuclear matter effects also contribute to the differences in the hadron suppression factor in Au+Au collisions. Figures 2(e) and 2(f) compare the R_{AA} for ϕ and π^0 and proton in central and peripheral d+Au collisions. For both centralities, the R_{AA} for ϕ

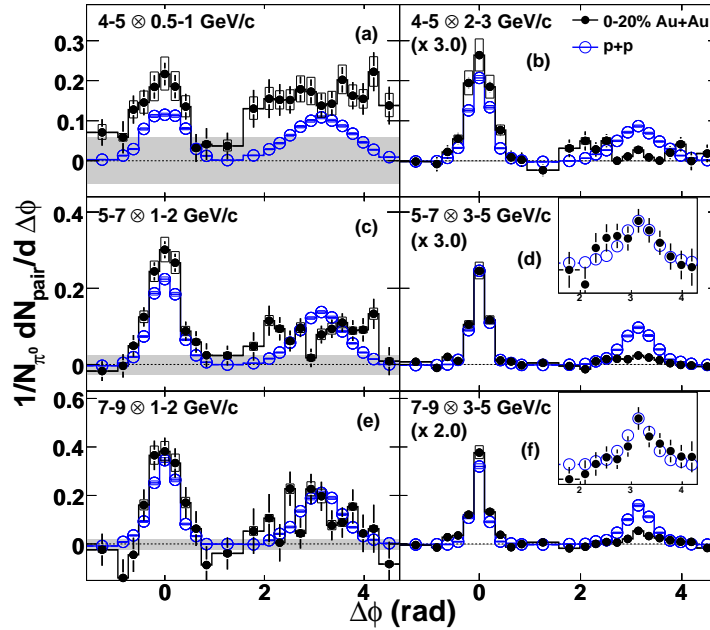


Fig. 3. Per-trigger jet pair yield versus $\Delta\phi$ for selected π^0 trigger and h^\pm partner p_T combinations ($p_T^t \times p_T^a$ in Au+Au (solid symbols) and $p+p$ (open symbols) collisions). The depicted Au+Au systematic uncertainties include point-to-point correlated background level and modulation uncertainties (shown respectively as gray bands and open boxes). For comparing shape, the insets show the away-side distributions scaled to match at $\Delta\phi = \pi$.

and π^0 are similar, indicating that cold nuclear matter effects are not responsible for the differences between them that are evident in Au+Au collisions.

3. Di-jet fragment azimuthal correlations

The study of the production of high transverse momentum hadrons in heavy ion collisions at RHIC provides an experimental probe of the QCD matter in the densest stage of the collisions [20]. In particular, two-hadron azimuthal correlations support the assessment of back-to-back, hard-scattered partons that propagate in the medium before fragmenting into jets of hadrons, thereby serving as a tomographic probe of the medium. It already was observed in di-hadron correlations from central Au+Au collisions that both the shape of the relative azimuthal angular distribution, and the yield of jet-like fragment pairs can depart significantly from those of $p+p$ collisions [21,22]. The underlying mechanisms for jet modification are not fully understood, but partonic energy loss by QCD radiative processes and collisions with medium constituents, as well as the evolution of the lost energy, should contribute to modifying the single and pair yields of hadrons associated with the jets.

Figure 3 shows the resulting per-trigger jet pair yields for selected trigger-partner combinations in $p+p$, and the 20% most central Au+Au collisions [23]. On the near side, the widths in central Au+Au are comparable to $p+p$ over the full p_T^t and p_T^a ranges, while the yields are slightly enhanced at low p_T , matching $p+p$ as p_T increases, while on the opposite, qualitatively we observe that for low p_T^t and low p_T^a the Au+Au jet peaks

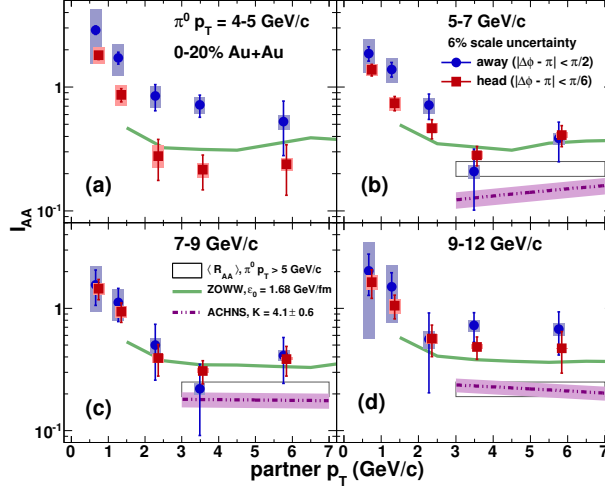


Fig. 4. Away-side I_{AA} for a narrow “head” $|\Delta\phi - \pi| < \pi/6$ selection (solid squares) and the entire away-side, $|\Delta\phi - \pi| < \pi/2$ (solid circles) versus h^\pm partner momentum for various $p+p$ trigger momenta. Calculations are shown from two different predictions for the head region in applicable p_T ranges [23]. A point-to-point uncorrelated 6% normalization uncertainty (mainly due to efficiency corrections) applies to all measurements.

are strongly broadened and non-Gaussian. In contrast, at high p_T^t and high p_T^a the yield substantially is suppressed, but the shape appears consistent with the measurement, as in the $p+p$ case. To study the shape modification measurement, we determined the away-side integrated yield. This modification of the determined jet yield in central collisions, shown in Figure 4, is measured by I_{AA} such that:

$$I_{AA} = \left(\int \frac{dN^{\text{pair}}}{N^t} \right)_{A+A} \bigg/ \left(\int \frac{dN^{\text{pair}}}{N^t} \right)_{p+p} \quad (2)$$

Away-side I_{AA} values for $p_T^t > 7$ GeV/c tend to fall with p_T^a for both the full away-side region ($|\Delta\phi - \pi| < \pi/2$) and for a narrower “head” selection ($|\Delta\phi - \pi| < \pi/6$) until $p_T^a \approx 2-3$ GeV/c, above which they become roughly constant. The yield enhancement at $p_T^t > 7$ GeV/c and $p_T^a < 2$ GeV/c is modest and occurs without significant modification of the shape. When p_T^t decreases, the away-side I_{AA} of the two angular selections differs as their shape changes. Figure 4 also shows the π^0 R_{AA} for $p_T > 5$ GeV/c [?]. The comparison reveals that I_{AA} is consistently higher than R_{AA} . This feature probably reflects a few competing effects. Selecting high- p_T trigger $p+p$ is expected to bias hard scattering towards the medium surface. Thus, away-side partons have a long average path length through the medium and consequently lose more energy. However, this feature does not require that the I_{AA} be lower than R_{AA} . The away-side conditional spectrum falls less steeply than the inclusive hadron spectrum and so the same spectral shift will more strongly reduce R_{AA} . More details on Figure 4 are given in Ref. [23].

4. Hadronization of bulk partonic matter

The anisotropic flow of hadrons was studied extensively in nucleus-nucleus collisions at the SPS and RHIC as a function of pseudorapidity, centrality, transverse momentum, and

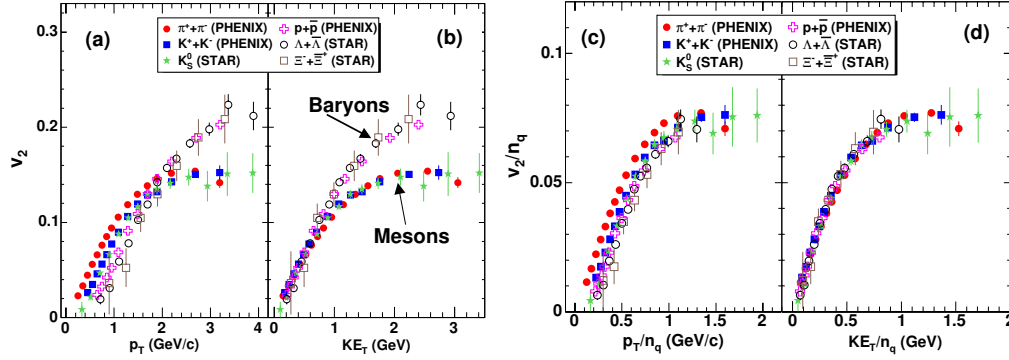


Fig. 5. Identified hadron anisotropy: Panels (a) as a function of transverse momentum p_T , panel (b) as a function of kinetic energy, panel (c) as a function of scaled p_T/n_q and, panel (d) as a function of scaled transverse kinetic energy $(m_T - \text{mass})/n_q$. n_q is the number of quarks valence in a given hadron (for mesons, $n_q = 2$; and, for baryons: $n_q = 3$). All data are from minimum-biased Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

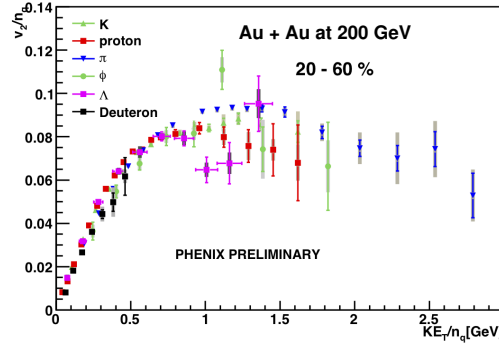


Fig. 6. panel (a) shows scaled v_2/n_q dependence of the transverse kinetic energy KE_T/n_q for ϕ mesons compared with different particle species obtained from Au+Au at $\sqrt{s_{NN}} = 200$ GeV (for mesons, $n_q = 2$; and, for baryons: $n_q = 3$).

energy [7,24,25]. In non-central collisions of heavy ions at high energy, the configuration of space anisotropy is converted into a momentum space anisotropy. The dynamics of the collision determine the degree of this transformation. For a symmetric system, like Au+Au, the second Fourier expansion is a good parameterization of anisotropy. At RHIC, a strong anisotropic flow (v_2) was observed for all hadrons measured. Comparing the data obtained at the mid-rapidity region presented by the STAR, PHOBOS, and PHENIX collaborations [7,25] to the hydrodynamic model [26] affording strong evidence that the originated medium behaves as a near ideal fluid.

Figure 5(a) and (b) show the anisotropic flow distributions, v_2 , for identified hadrons obtained in minimum-bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [27]. The values for neutral Kaons (K_s^0), lambdas (Λ), and the cascade (Ξ) are taken from Ref.[28]. In the lower p_T region, $p_T \leq 2$ GeV/c, the value of v_2 is inversely related to the mass of the hadron, that is, it is characteristic of hydrodynamic collective motion in operation. At the intermediate p_T region, the dependence is different. Instead of a mass dependence,

there seems to be a hadron type dependence, clear splitting into a meson branch and a baryon branch. This observation is well demonstrated in Figure. 5(b) when v_2 is shown as a function of the transverse kinetic energy. To include the effect of collective motion, the p_T was transferred to the transverse kinetic energy $KE_T \equiv m_T - \text{mass} = \sqrt{p_T^2 + m^2} - m$ where m is the mass of the particle. To demonstrate the scaling properties of v_2 , the following transformation was performed in which we scaled the measured v_2 by the number of valence quarks in a given hadron. For mesons and baryons, respectively, they are $n_q = 2$ and 3. The p_T and KE_T also were scaled with the same n_q ; Figures 5(c) and 5(d), respectively, depict the outcome. All of the hadron v_2 scaled nicely up to $(m_T - \text{mass})/n_q \sim 1.2$. At high- p_T , the values of v_2 appear to fall. These observations about scaling reveal that before hadronization, quarks already have acquired the collective motion v_2 , and that when they coalesce, the v_2 is passed to newly formed hadrons.

Strange quark dynamics is a useful probe of the dense matter created at RHIC. Enhanced strangeness [29] was proposed as an important signal for the formation of the Quark-Gluon Plasma (QGP) in nuclear collisions. The dominant production of $s\bar{s}$ pairs via gluon-gluon interactions may lead to a strangeness (chemical and flavor) equilibration time, comparable to the lifetime of the QGP whereas the strangeness equilibration time in a hadronic fireball is much longer than the fireball's lifetime. Therefore, the subsequent hadronization of the QGP is expected to enhance the production of strange particles. In particular, it was argued that with the formation of QGP, the production of ϕ mesons is heightened. Furthermore, ϕ mesons could retain information on the condition of the hot plasma at hadronization because they interact weakly in the hadronic matter [30]. The measurement of ϕ mesons has been of great interest in the study of collision dynamics and the properties of the dense matter created at RHIC [31–33]. Figure 6 shows the elliptic flow v_2 normalized by the valence quarks for ϕ mesons from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Experimental data [34] of $K^+ + K^-$ and $p + \bar{p}$ are presented for comparison. In the intermediate p_T region of $p_T/n_q > 0.6$ GeV/c, the elliptic flow of charged kaons, protons, and ϕ mesons seems to satisfy the valence quarks scaling. This result implies that u, d and s quarks in the initial partonic matter formed in relativistic heavy ion collisions develop significant collectivity with a strength characterized by v_2/n_q .

5. New era of heavy flavor measurements : PHENIX Silicon Vertex Tracker

In December 2010, the PHENIX Collaboration open new era for measuring heavy flavor at RHIC by installing new detector called the Silicon Vertex Tracker (VTX) [35]. The VTX is under commissioning with beam $p+p$ at 500 GeV, and it will be ready to take data this year on Run 11 at RHIC. Our main physics motivation is to enable measurements of heavy-flavor production (charm and beauty) in $p+p$, d+Au and Au+Au collisions. Such data will illuminate the properties of the matter created in high-energy heavy-ion collisions. The measurements also will reveal the distribution of gluons in protons from $p+p$ collisions. The VTX detector consists of four layers of barrel detectors and covers $|\eta| < 1.2$, and almost a 2π in azimuth. The inner two silicon barrels consist of silicon pixel sensors. Figure 7(a) shows ladders of a half barrel of a pixel detector; their technology accords with that of the ALICE1/LHCB sensor-readout hybrid. The outer two barrels are silicon stripixel detectors with a new "spiral" design, and a single-sided sensor with 2-dimensional (X, U) readout. Figure 7(b) shows the ladders of half barrel of stripixel detector. Figure 7(c) shows VTX detector including the readout, assembled and surveyed at the laboratory. Figure 7(d) shows the VTX installed around PHENIX's interaction

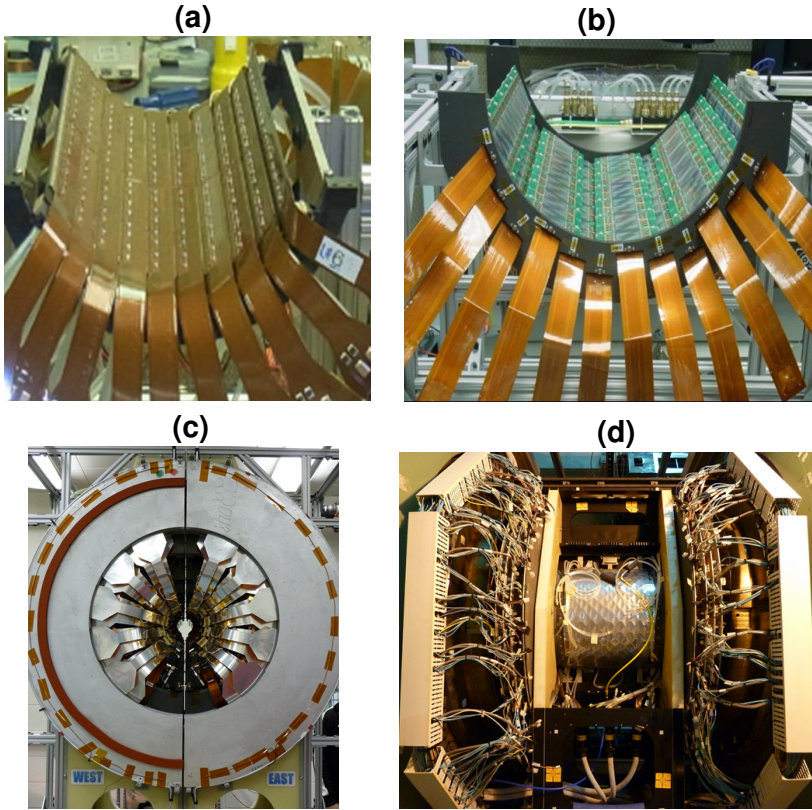


Fig. 7. The PHENIX Silicon Vertex Tracker. Panel (a) and (b) show the ladders of half barrels of pixel and stripixel detectors, respectively. Panel (c) shows VTX detector including the readout, assembled and surveyed at the laboratory. Panel (d) shows VTX installed around the PHENIX's interaction point and cabled to the readout, in December 2010.

point and cabled to the readout, in December 2010.

6. Summary

Studies of jets and anisotropic flow at RHIC have produced very important, exciting results. These observations are open to different interpretations and continue to test different hypotheses, but, at the same time it seems undisputable that in Au+Au collisions at RHIC we created the deconfined and mostly thermalized matter. The PHENIX experiment is assembling a full picture of the results through developments in several directions: higher- p_T , for different particle species, correlations, and full jet reconstruction. This year, PHENIX opens new era to study the properties of the medium, through identifying non-photon electrons from decays of particles carrying charm or beauty quarks, by installing a new detector called Silicon Vertex Tracker, in December 2010. This new detector is under commissioning and will take data from RHIC Run-11, this year.

References

- [1] S. Shuryak, Phys. Rep. **61**, (1980) 71; L. McLerran, Rev. Mod. Phys. **58**, (1986) 1021.

- [2] H. Satz, Nucl. Phys. A **715** (2003) 3c.
- [3] F. Karsch, Nucl. Phys. A **698** (2002) 199c.
- [4] J. Hofman, *et al.*, in Bear Mountain Workshop, New York, December 19974; H.G. Baumgardt, *et al.*, Z. Phys. A **273** (1975) 359.
- [5] B.I. Abelev *et al.* Phys. Lett. B **655** (2007) 104; S.S. Adler *et al.* Phys. Rev. Lett. **98** (2007) 172302; S.S. Adler *et al.* Phys. Rev. Lett. **96** (2006) 202301; S.S. Adler *et al.* Phys. Rev. Lett. **91** (2003) 072303.
- [6] I. Vitev, Phys. Lett. B **639** (2006) 3845.
- [7] I. Arsene *et al.* Nucl. Phys. A **757** (2005) 1; B. B. Back *et al.* Nucl. Phys. A **757** (2005) 28; J. Adams *et al.* Nucl. Phys. A **757** (2005) 102; K. Adcox *et al.* Nucl. Phys. A **757** (2005) 184;
- [8] R. Nouicer e-Print arXiv-nucl-ex/0901.0910 (to be published in the European Physical Journal).
- [9] I.G. Bearden *et al.* Phys. Rev. Lett. **93** (2004) 102301.
- [10] J.D. Bjorken, Phys. Rev. D **27** (1983) 140; X.N. Wang *et al.* Phys. Rev. Lett. **68** (1992) 1480; and M. Gyulassy *et al.* Phys. Lett. B **243** (1990) 432.
- [11] J.J. Gaardh *et al.* Nucl. Phys. A **734** (2004) 13.
- [12] C. Albajar *et al.* Nucl. Phys. B **355** (1990) 261; J. Adams *et al.* Phys. Rev. Lett. **91** (2003) 172302.
- [13] I. Vitev *et al.* Nucl. Phys. A **715** (2003) 779; X.-N. Wang, Phys. Lett. B **595** (2004) 165; X.-N. Wang, Phys. Lett. B **579** (2004) 299; C.A. Salgado *et al.* Phys. Rev. D **68** (2003) 014008.
- [14] I. Vitev *et al.* Phys. Rev. Lett. **89** (2002) 252301.
- [15] I. Vitev, J. Phys. G **30** (2004) S791.
- [16] S.S. Alder *et al.* Phys. Rev. Lett. **98** (2007) 17230; S.S. Alder *et al.* Phys. Rev. Lett. **96** (2006) 032001; S.S. Alder *et al.* Phys. Rev. Lett. **96** (2006) 032301.
- [17] J. Adams *et al.* Phys. Rev. Lett. **94** (2005) 062301; A.P. Suaide Braz. Jour. of Phys. **37** (2007) 2c.
- [18] J. Adams *et al.* Phys. Lett. B **612**, 181 (2005) 181; S. Blyth *et al.* proceedings of International Conference on Strangeness in Quark Matter, Los Angeles, California, 26 - 31 March 2006; e-Print arXiv-nucl-ex/060801.
- [19] A. Adare *et al.* e-Print arXiv-nucl-ex/1004.3532.
- [20] P. Jacobs *et al.*, Prog. Nucl. Phys. **54**, (2005) 443.
- [21] J. Adams *et al.*, Phys. Rev. Lett. **95** (2005) 152301.
- [22] A. Adare *et al.*, Phys. Rev. C **78** (2008) 014901.
- [23] A. Adare *et al.*, Phys. Rev. Lett. **104**, (2010) 1122.
- [24] C. Alt *et al.* Phys. Rev. C **68** (2003) 034903; and references therein.
- [25] R. Nouicer *et al.* J. Phys. G **34** (2007) S887.
- [26] T. Hirano, Acta Phys. Polon. B **36** (2005) 187; U.W. Heinz e-Print arXiv-nucl-th/0512051.
- [27] A. Adare *et al.*, Phys. Rev. Lett. **98** (2007) 162301; M. Shimomura *et al.*, J. Phys.: Conf. Ser. **270** (2011) 012041.
- [28] J. Adams *et al.*, Phys. Rev. Lett. **92**, 052302 (2004); J. Adams *et al.*, Phys. Rev. Lett. **95**, 122301 (2005).
- [29] J. Rafelski *et al.*, Phys. Lett. B **111**, 101 (1982); P. Koch *et al.*, Phys. Rep. **142**, 167 (1985).
- [30] A. Shor, Phys. Rev. Lett. **54**, 1122 (1985).
- [31] J. Adams *et al.*, Phys. Lett. B **612**, 181 (2005).
- [32] S. S. Adler *et al.*, Phys. Rev. C **72**, 014903(2005).
- [33] C. Nonaka *et al.*, Phys. Lett. B **583**, 73 (2004).
- [34] S. S. Adler *et al.*, Phys. Rev. Lett. **91**, 182301 (2003).
- [35] R. Nouicer *et al.*, Journal of Instrumentation (JINST), **4** (2009) P04011; R. Nouicer *et al.*, Nuclear Instruments and Methods in Physics Research B **261** (2007) 10671071; Z. Li, Nuclear Instruments and Methods in Physics Research A **518** (2004) 738; M. Baker *et al.*, Proposal for a Silicon Vertex Tracker (VTX) for the PHENIX Experiment, BNL-72204-2004, Physics Dept. BNL (2004).